GG 611 Big Gulp
Fall 2014

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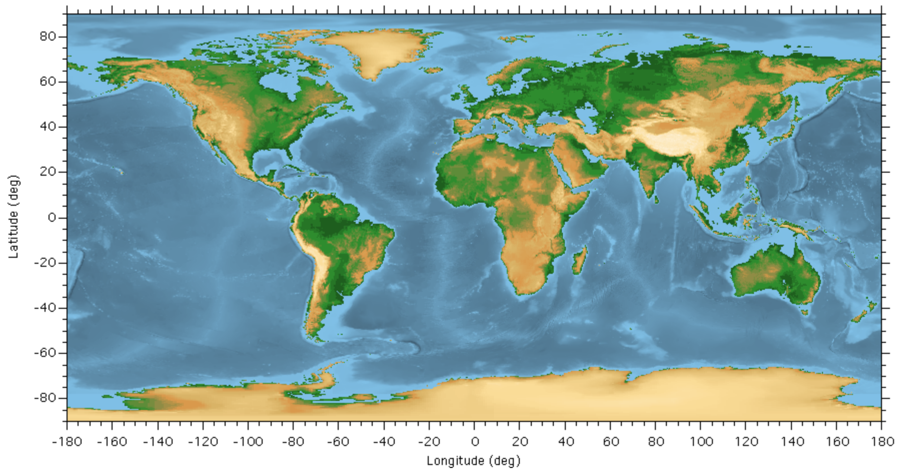
Gravity, the Geoid, and Mantle Dynamics

Lecture: Plate Tectonics & Mantle Convection



Francis Bacon (1561-1626)

Ben Franklin (1706-1790)

The Known World, ~1700

Was the Atlantic once closed?

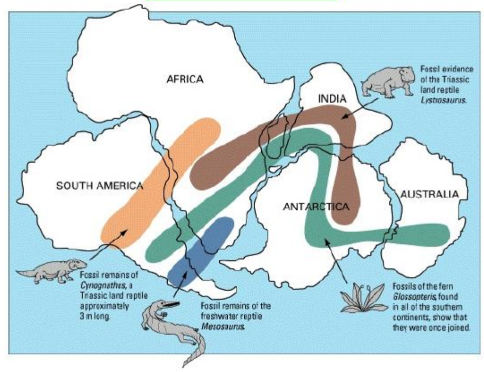
If so, how could this be?

Alfred Wegener
(1880-1930)

The two sides of the Atlantic:

Matching Shapes
Matching Rock Types
Matching Fossils
Patterns of Uplift

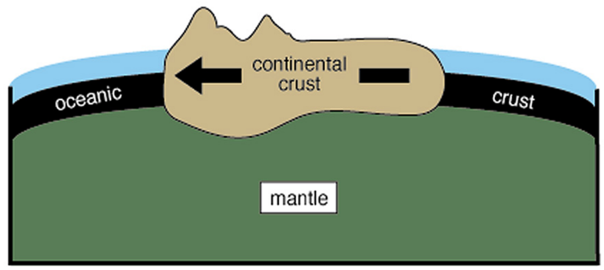
Fossil Distributions



Wegener's Idea: *The Origin of Continents and Oceans* (1915)

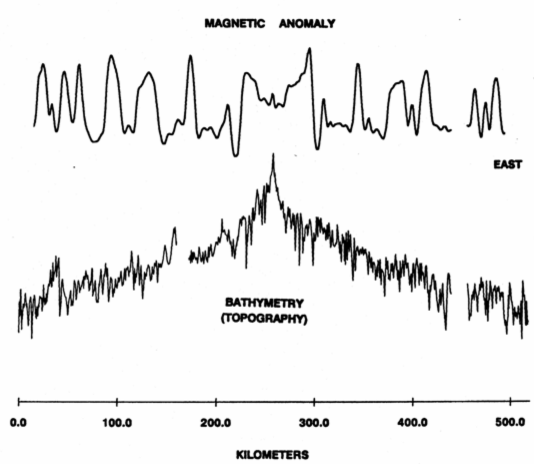
Continental Drift:
The continents plowed through the oceanic crust

Problem:
Wegener did not describe the forces that caused continents to move!



Wegener's proposal that continents plowed through oceanic crust was not accepted by other geologists.

1950s - Magnetic Surveys of the Seafloor

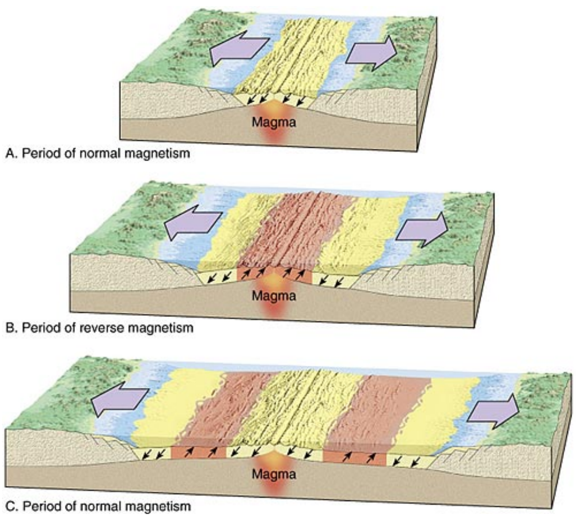


Magnetic Anomaly:
symmetric about ridge

Seafloor Bathymetry:
descends away from ridge

1960s: The development of **Plate Tectonics**

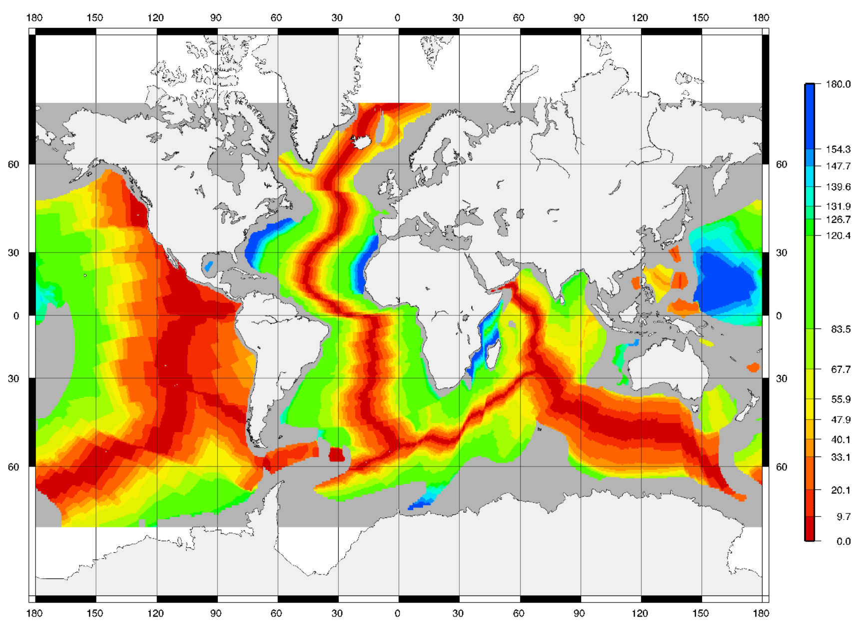
Harry Hess, 1962: “A History of the Ocean Basins”
Seafloor spreading allows plates to move



New seafloor is being created as the seafloor spreads

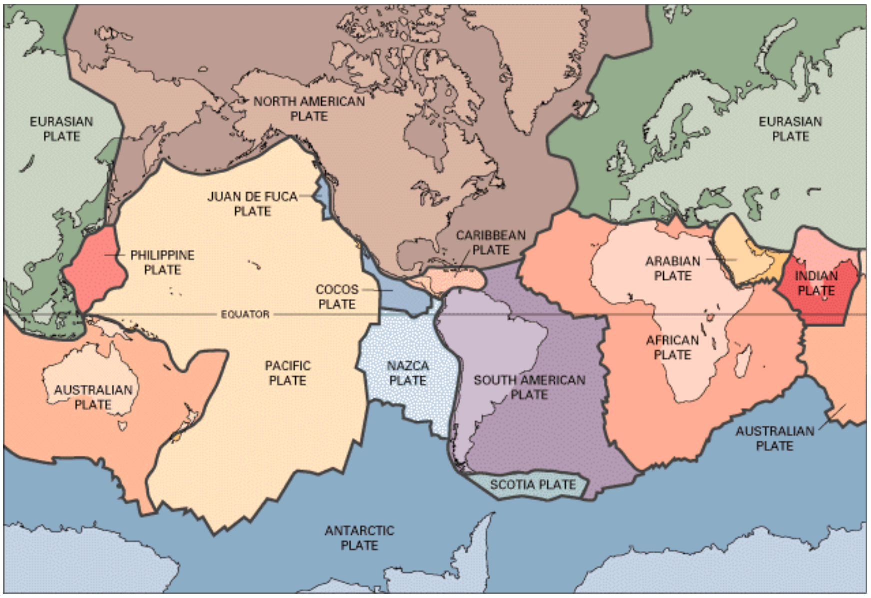
The magnetic field is "frozen" in the newly-created seafloor.

Mapping Seafloor Ages



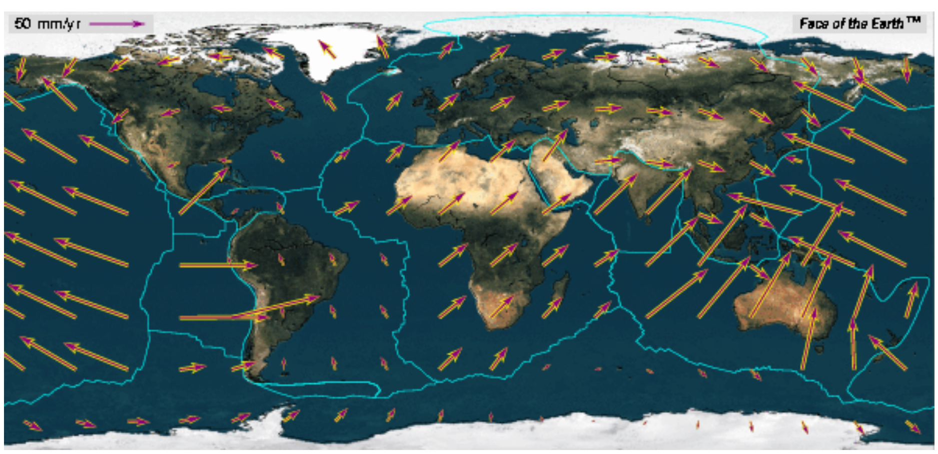
Oldest Seafloor = 180 Million Years!

Earth's Tectonic Plates



Biggest Plate: Pacific Plate (10,000 km across)
Smallest Plate: Juan de Fuca (300 km across)
All sizes in between!

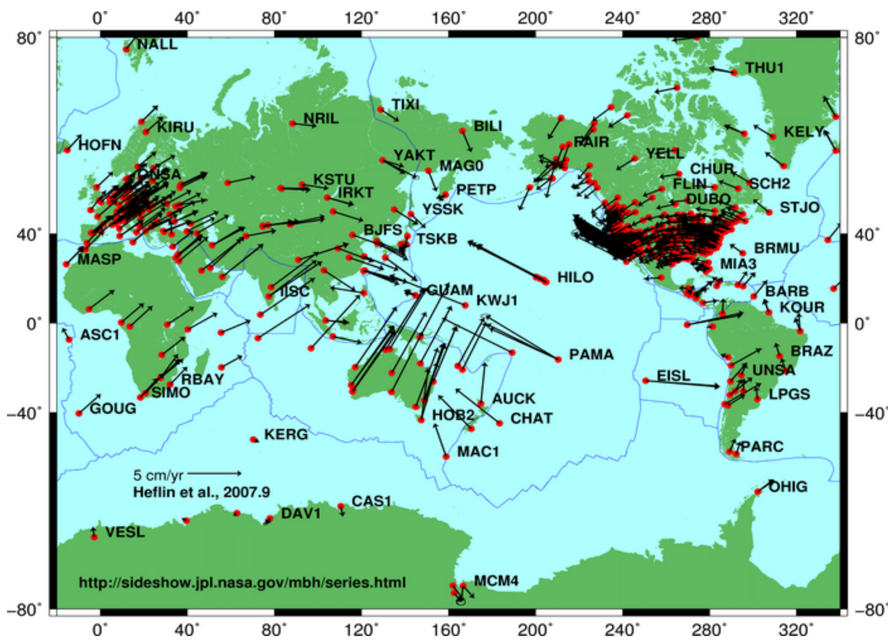
How Fast do the Plates Move?



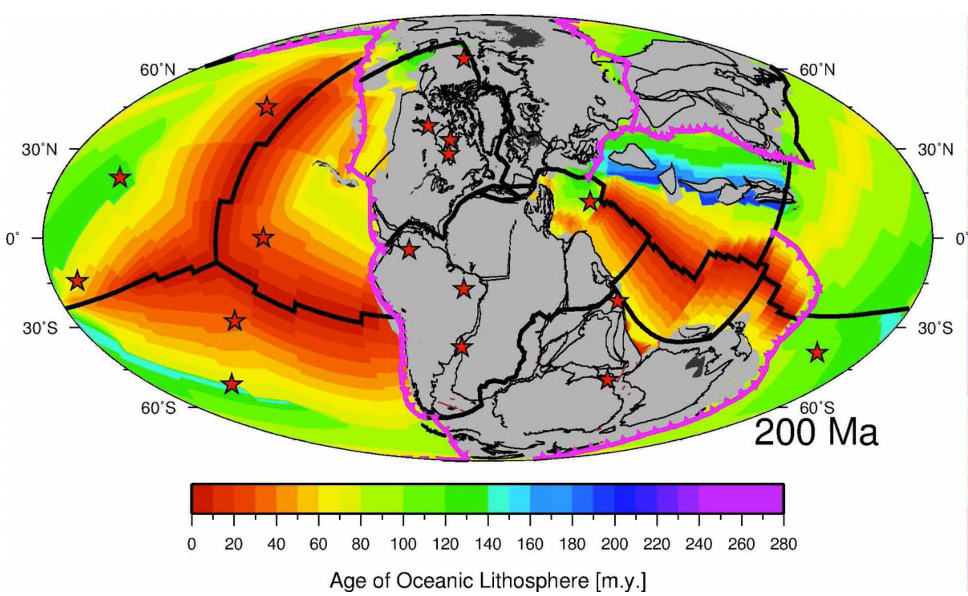
<u>Plate Speeds</u>

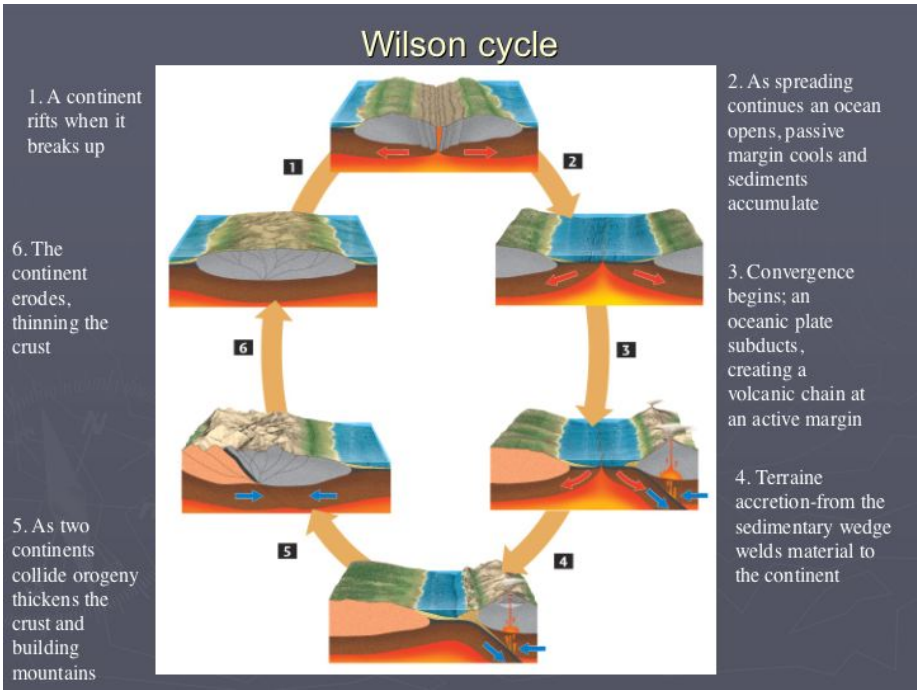
Atlantic Basin:	1-2 cm/yr
Indian Basin:	3-7 cm/yr
Pacific Basin:	5-10 cm/yr

Plate Motions can now be observed using GPS



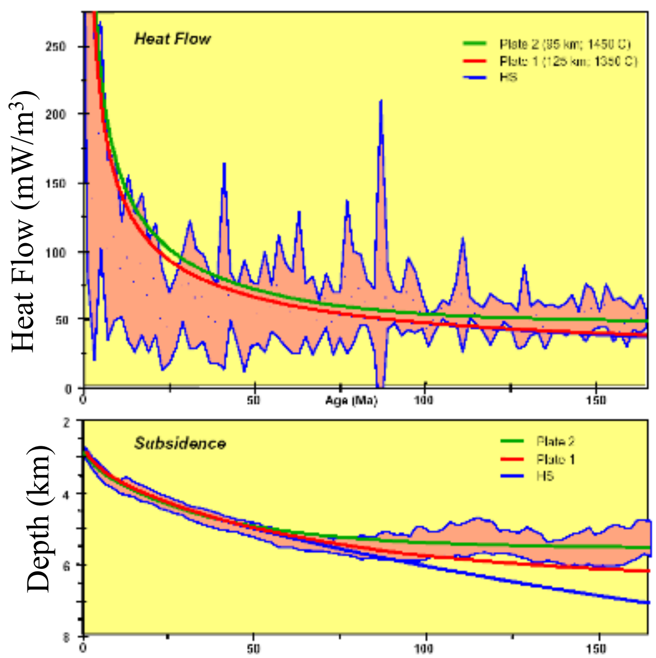
Tectonic Reconstruction of the Ocean Basins: **Seafloor Ages**





The Wilson Cycle: Supercontinents repeatedly form and disperse

Seafloor heat flow and depth decrease with seafloor age [*Stein & Stein*, 1992]



Seafloor Age (Myr)

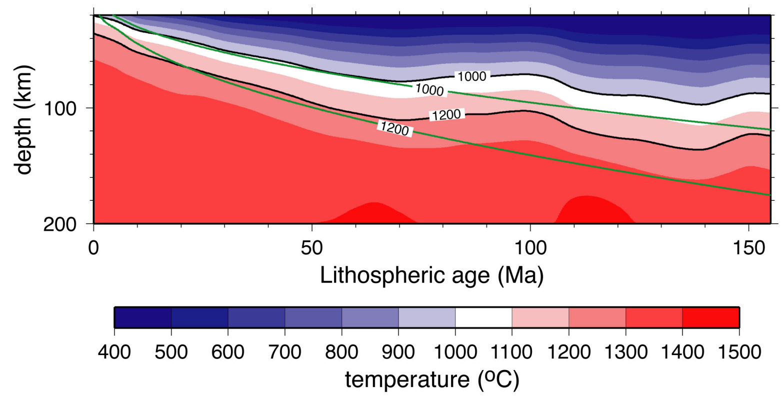
Heat flux is proportional to: 1/sqrt(age)

Seafloor depth below the ridge crest is proportional to: sqrt(age)

Temperatures across a spreading ridge

Hot:
Low-density rocks are elevated to make a ridge

Cold:
High-density rocks make deep seafloor



Thermal boundary layer thickness: $h = 2.3 \text{ sqrt}(\kappa t)$ where
t is seafloor age
$\kappa=10^{-6}$ m^2/s is the thermal diffusivity

What drives the plate motions?
WHY do the plates move?

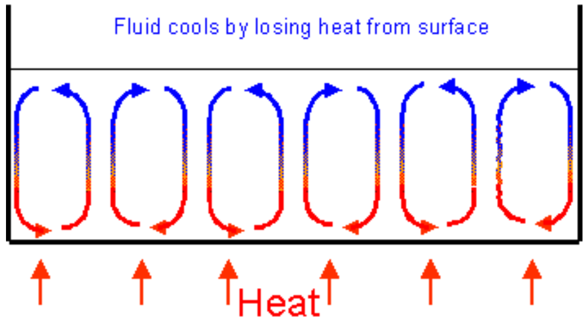
The Earth loses heat through <u>CONVECTION</u>

Examples of Convection

Lava lamp

Boiling water

How Convection Works



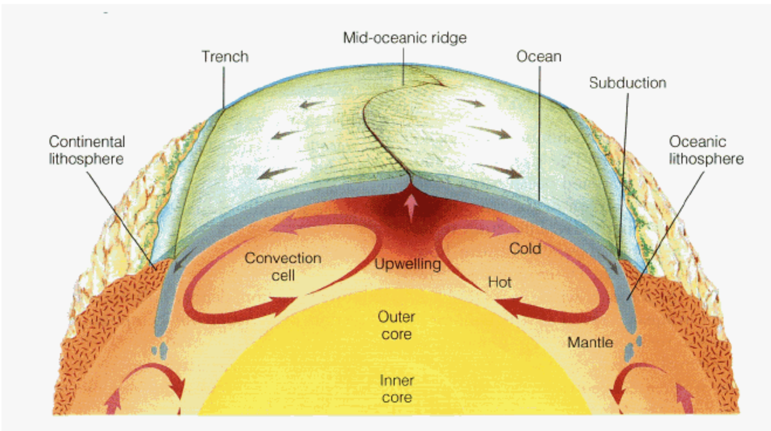
Cold Fluid Sinks

Hot Fluid Rises

Convection cell
Warm, low density fluid rises
Cool, high density fluid sinks

Convection is the fastest way for the Earth to get rid of heat

Mantle Convection and Plate Tectonics



UPWELLING beneath spreading ridges

DOWNWELLING beneath subduction zones

THE PLATES surface expression of mantle convection

The Rayleigh Number is a dimensionless parameter that measures the vigor of convection:

$$Ra = \frac{\rho g \alpha \Delta T D^3}{\kappa \eta}$$

$\rho =$ density (3300 kg/m^3)
$g =$ gravity (10 m/s^2)
$\alpha =$ thermal expansivity (3×10^{-5} K^{-1})
$\Delta T =$ Temperature contrast across mantle (3000 K)
$D =$ Depth of Mantle (2860 km)
$\kappa =$ Thermal diffusivity (10^{-6} m^2/s)
$\eta =$ Mantle viscosity (10^{21} Pa s)

Using these parameters: Ra ~ 7×10^7
Convection occurs if Ra is larger than a critical value Ra_{cr}
For convection in a layer, $Ra_{cr} = 657$

Mantle Convection: How Vigorous?

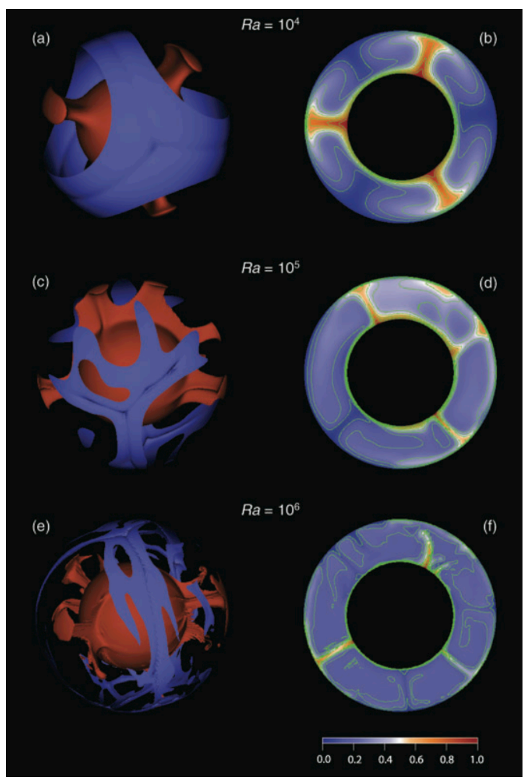
Deschamps et al., 2010

Style and vigor of convection changes with Ra

Boundary layer thickness $h \sim Ra^{-\frac{1}{3}}$

Plate velocity $v_p \sim Ra^{\frac{2}{3}}$

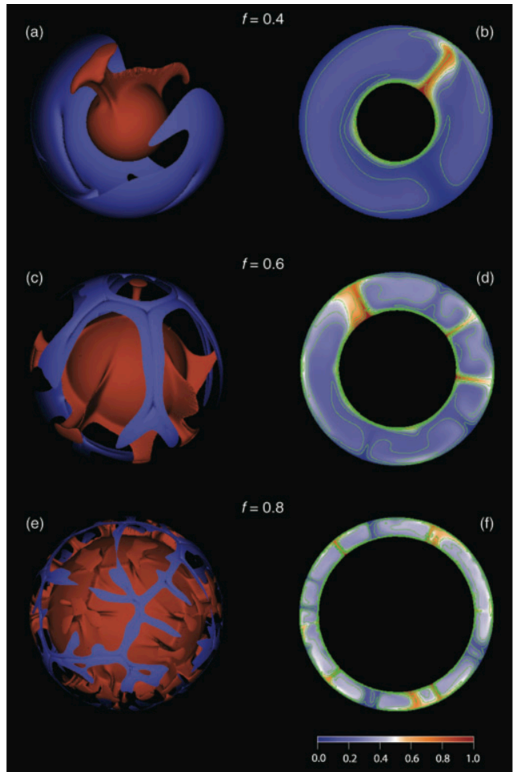
Mantle heat flow $Q \sim Ra^{\frac{1}{3}}$



Mantle Convection: Effect of Core Size Ra =10^5

Deschamps et al., 2010

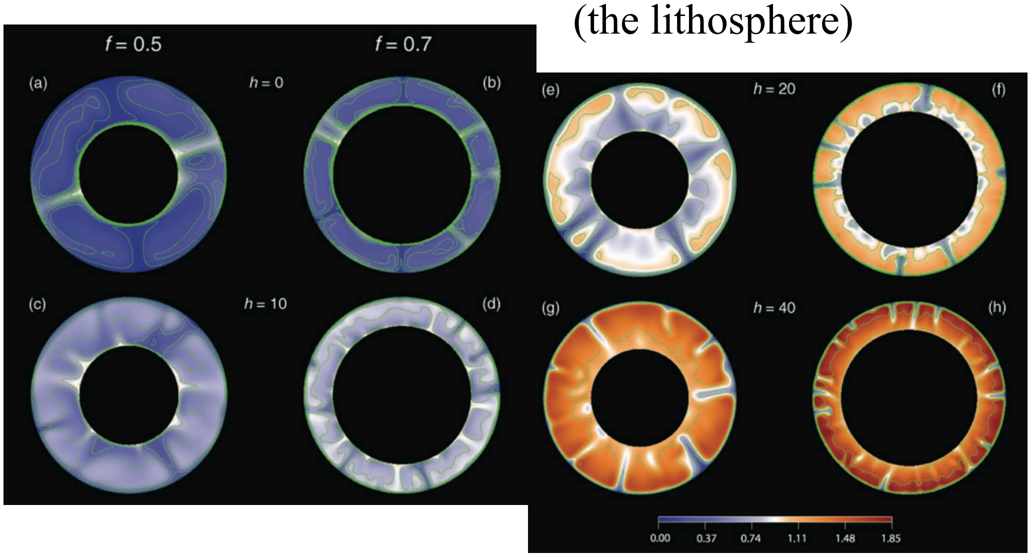
Convection cells form with an aspect ratio greater than 1

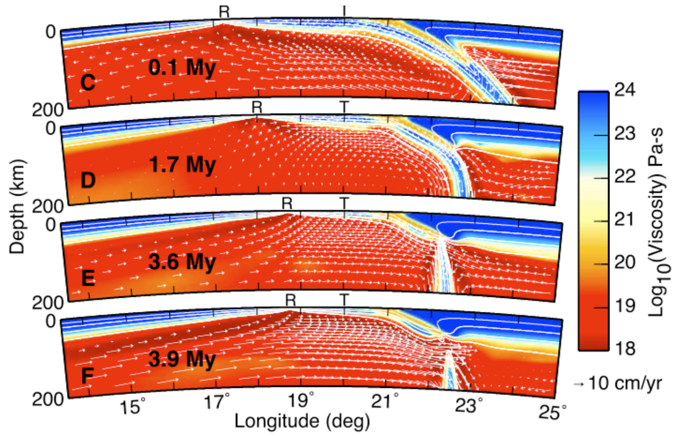


Mantle Convection: Effect of Internal Heating

Deschamps et al., 2010

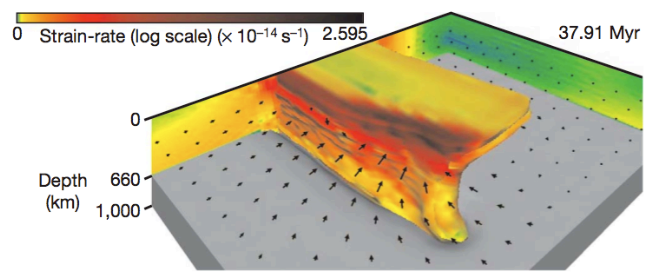
Internal heating increases the importance of the top boundary layer (the lithosphere)





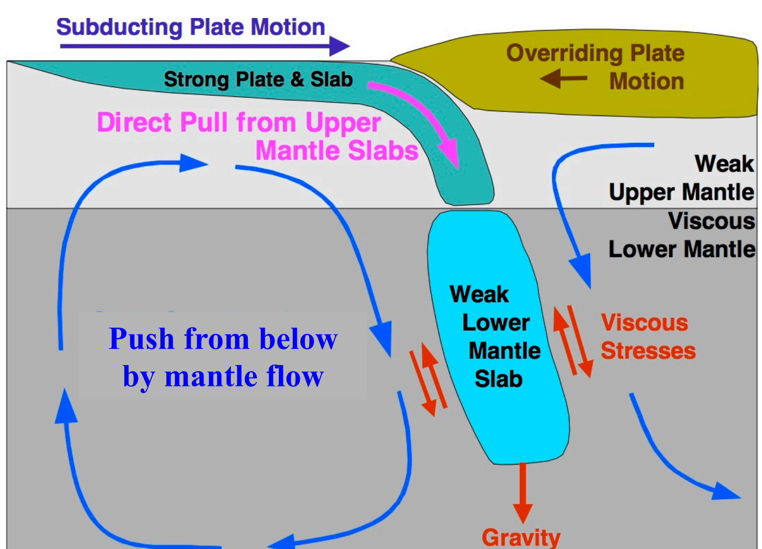
Subduction and Slabs form a crucial part of convection on Earth

Burkett & Billen [2009]



Schellart et al [2007]

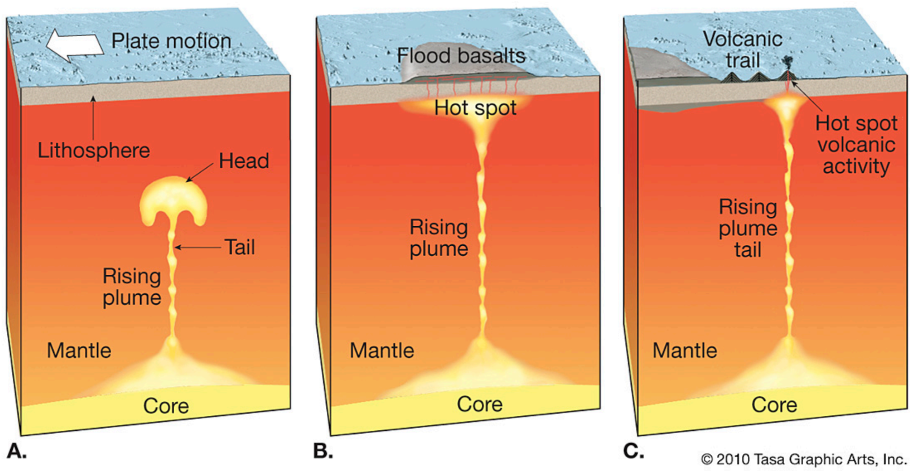
What drives the plate motions?



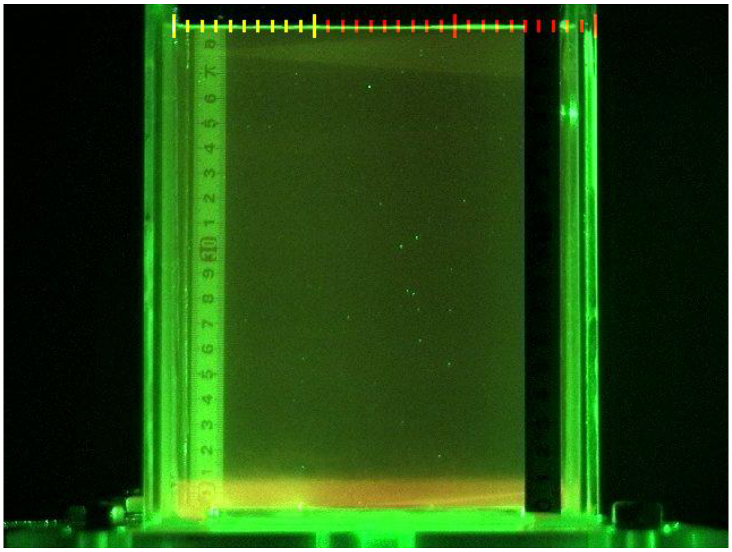
Conrad & Lithgow-Bertelloni [2002]

Two Main Forces:
1. **Direct pull from subducted slabs**
2. **Push from below by mantle flow**

Mantle Plumes and Hotspots

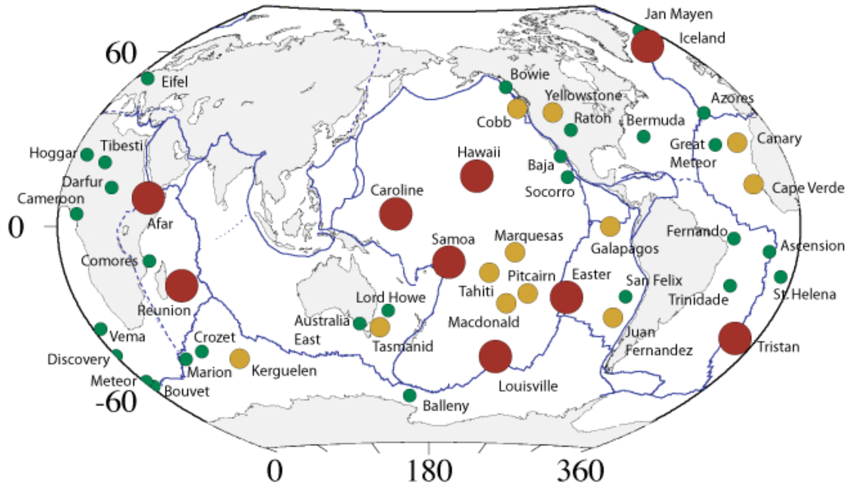


Mantle plumes explain volcano chains within plate interiors.
Plumes rise from the lower boundary layer of convection.



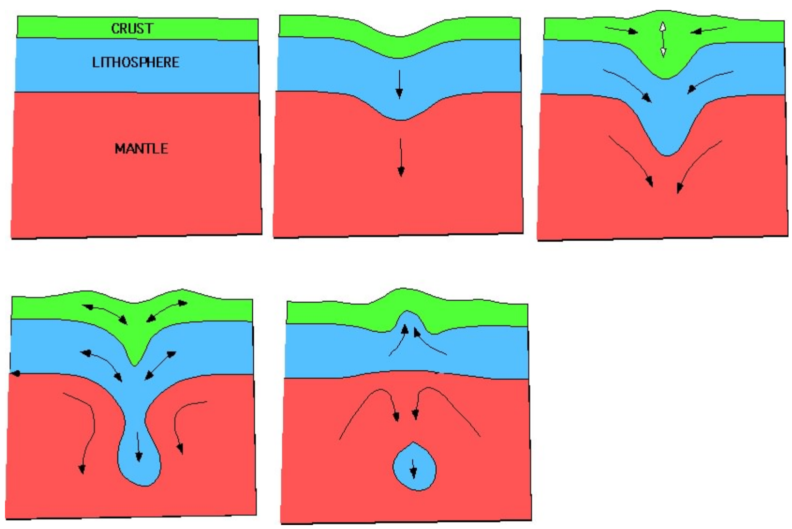
A Plume Experiment in Corn Syrup

Mantle Plumes and Hotspots



There are likely only about 9 major mantle plumes (the big red dots):

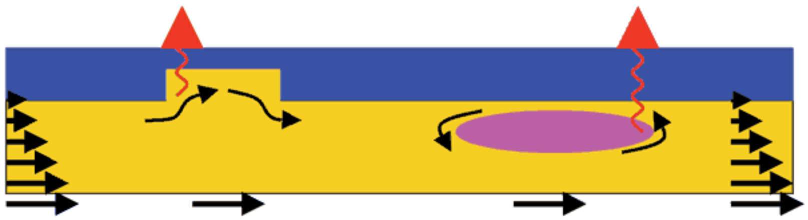
Small-Scale Convection



Like an upside-down plume:
Cold "drips" sink down into the mantle.

Explains some mountains and minor volcanism.

Shear-Driven Upwelling



Like a plume moving sideways:
Shearing beneath the tectonic plates produces
upwelling and volcanism (if viscosity is heterogeneous)

Explains some minor volcanism [*Conrad et al.,* 2011].

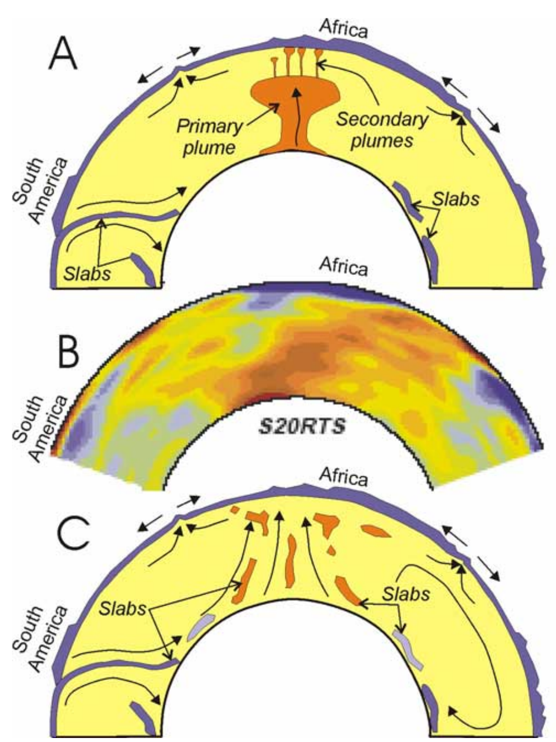
Superplumes?

Two giant slow seismic anomalies are observed beneath Africa & the Pacific

These may represent major upwellings in the mantle.

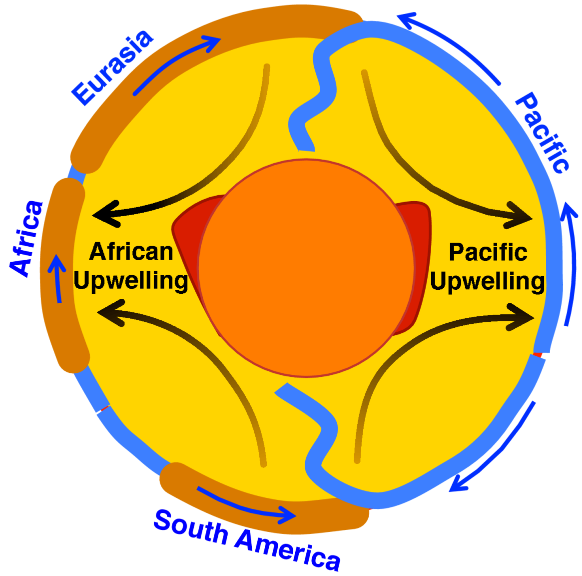
Tomography across Africa

Plume Cluster?



The superplumes appear to be stable.

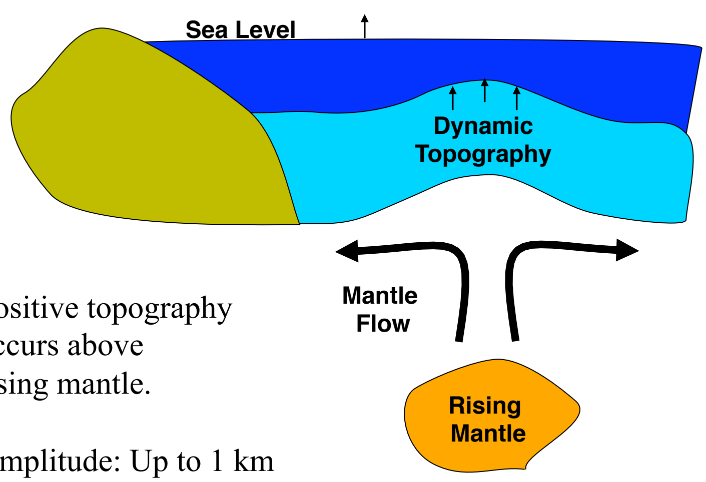
They may organize the pattern of flow in the mantle:



Conrad et al. [2013]

Mantle Flow causes surface uplift and subsidence.

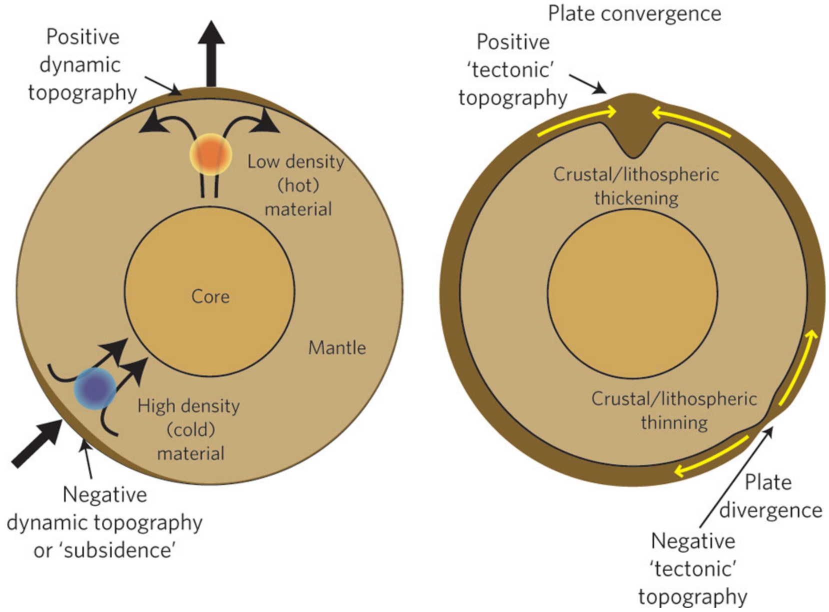
This topography is called "Dynamic Topography".



Positive topography occurs above rising mantle.

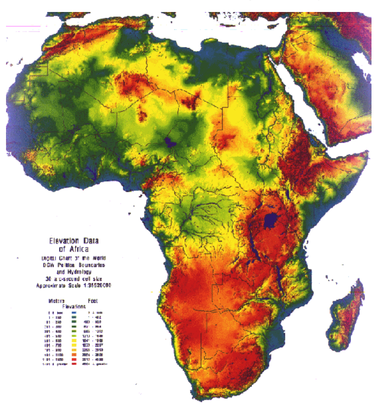
Amplitude: Up to 1 km

Dynamic Topography / Tectonic Topography

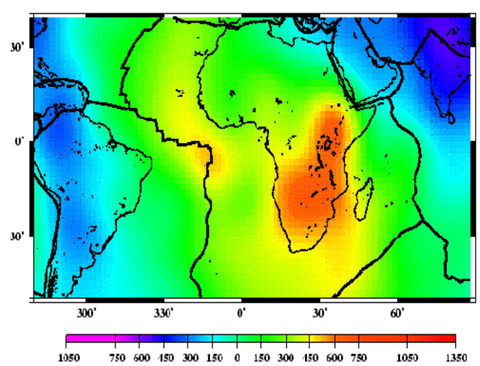


Dynamic Topography in Africa

Observed Topography



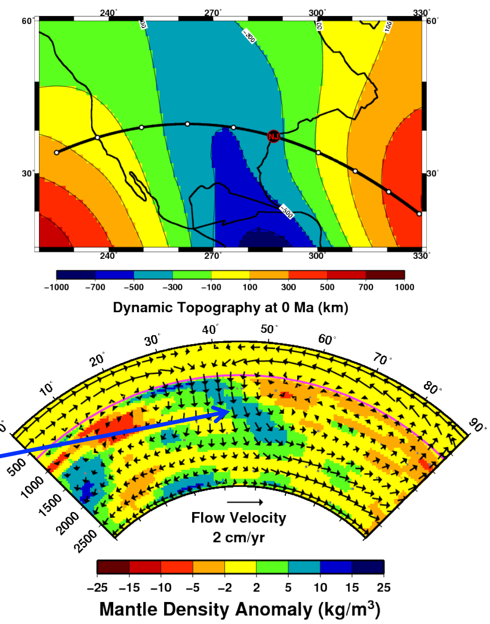
PredictedTopography



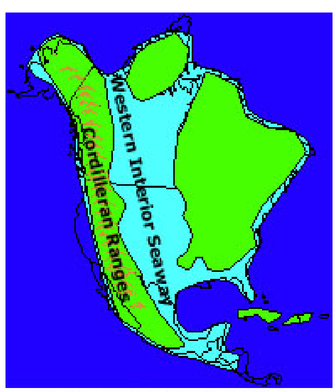
Dynamic Topography in North America

Downwelling beneath the Eastern US depresses the surface

Farallon Slab



Dynamic topography caused the Western Interior Seaway



Maximum extent of the Western Interior Seaway about 100 million years ago

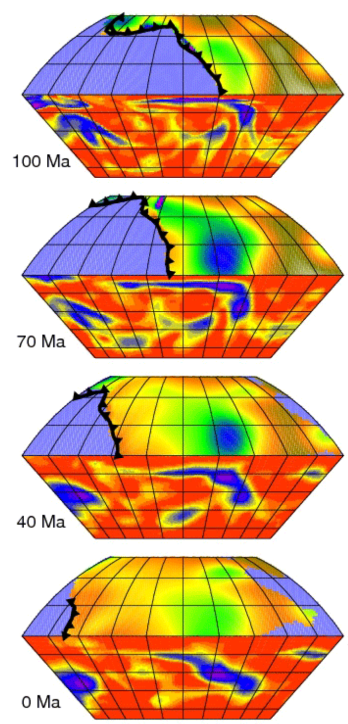
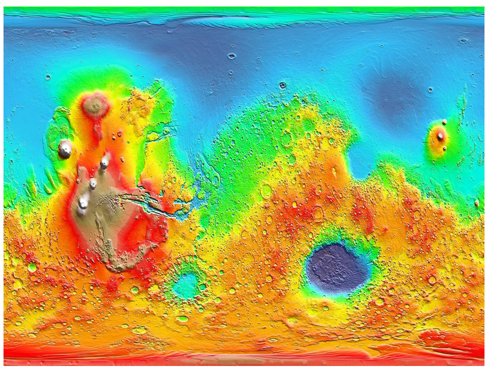


Plate Tectonics and Convection on other Planets?

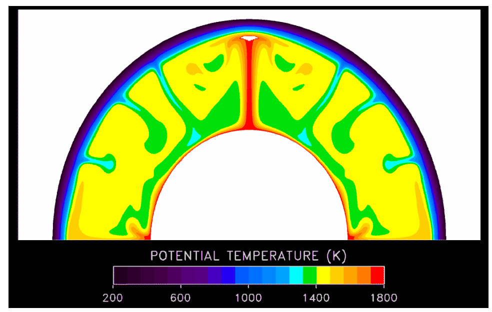
Moon, Mars, Venus, Mercury: Surfaces are much older than Earth's: Probably no plate tectonics

Instead, mantle convection may take a different form

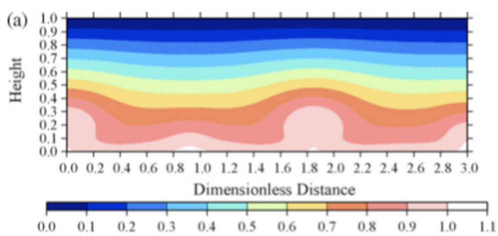
Mars Topography



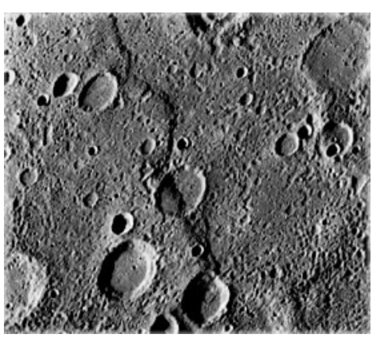
Model of Mars Convection



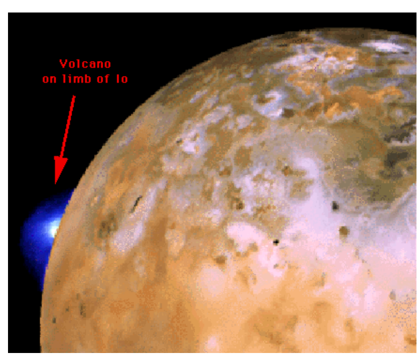
Mercury: Low Ra

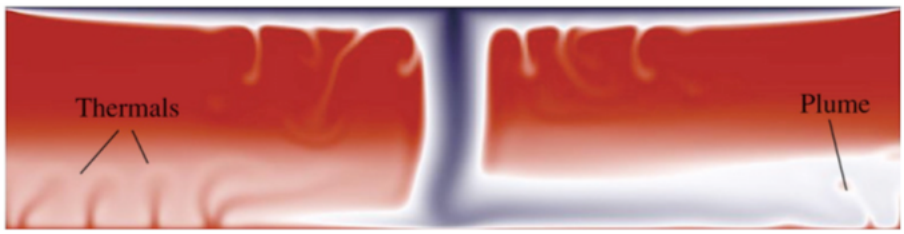


Redmond & King 2007



Io: High Ra



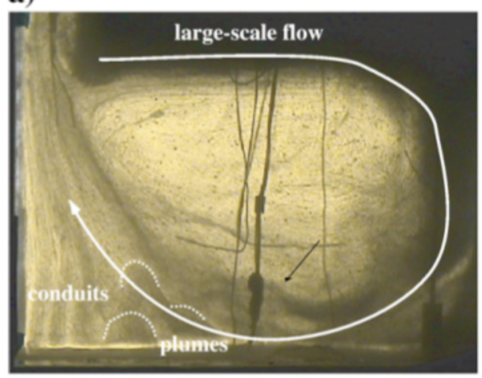


Venus:

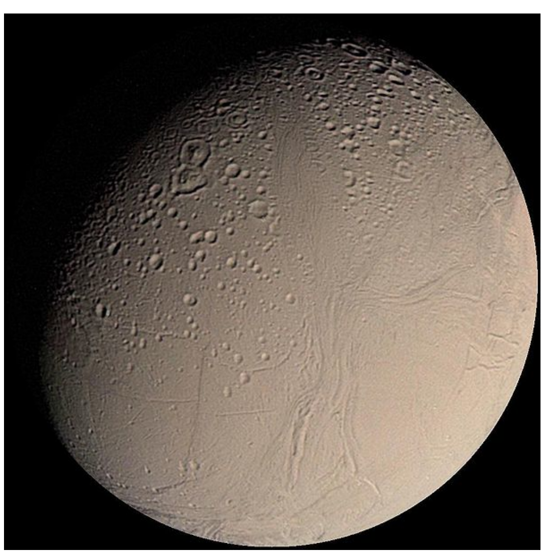
**No plate tectonics,
but the entire lithopshere
sometimes sinks into
the mantle, resurfacing
the entire planet.**

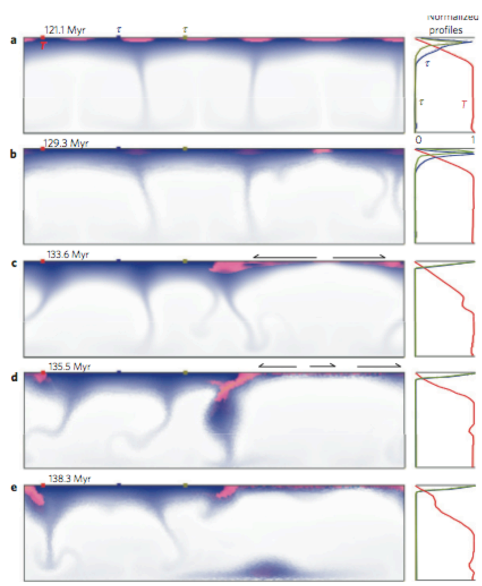
Robin et al., 2007

a)



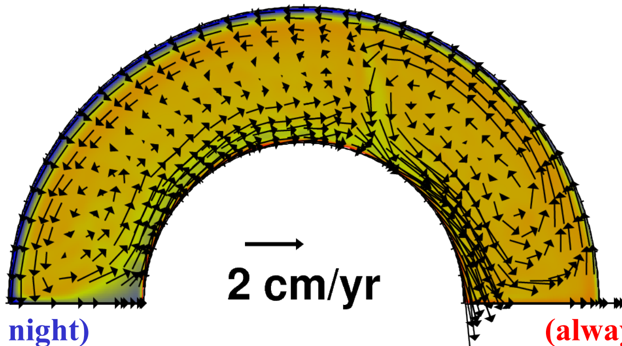
Enceladus: Convection in solid ice





Exoplanets: Many different styles!

Tidally-locked example



COLD SIDE (always night)

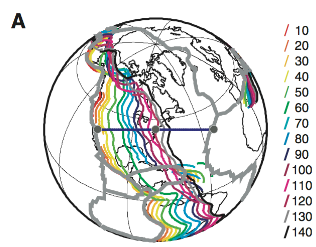
HOT SIDE (always day)

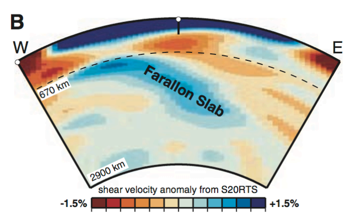
van Summeren, Conrad, & Gaidos, 2011

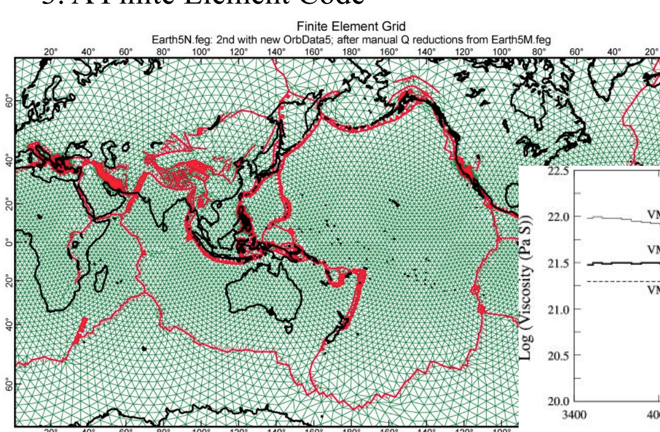
Numerical Models of Mantle Convection

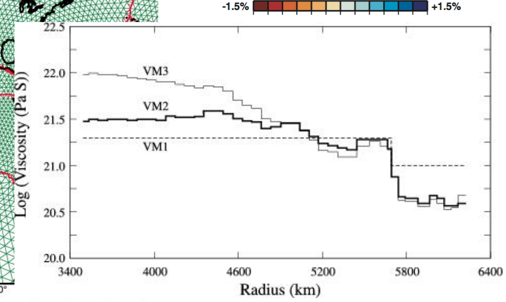
Input:

1. Mantle Densities
   (from seismic tomography)
2. Mantle Viscosity Structure
   (from postglacial rebound)
3. A Finite Element Code



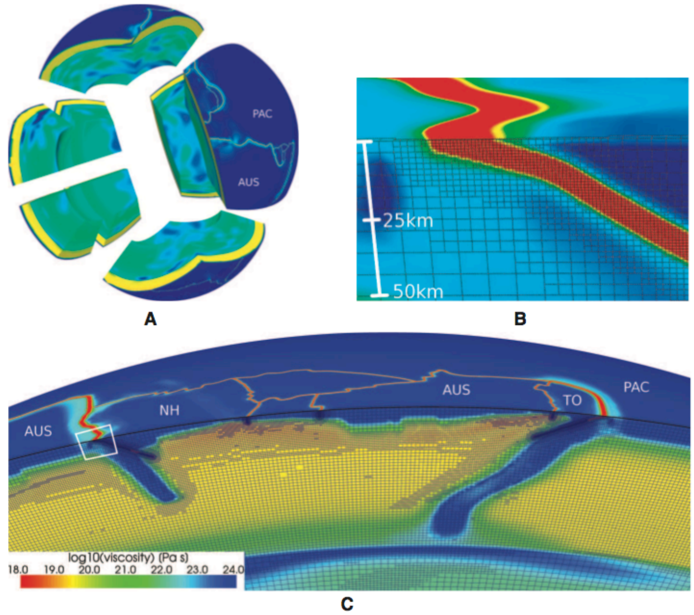




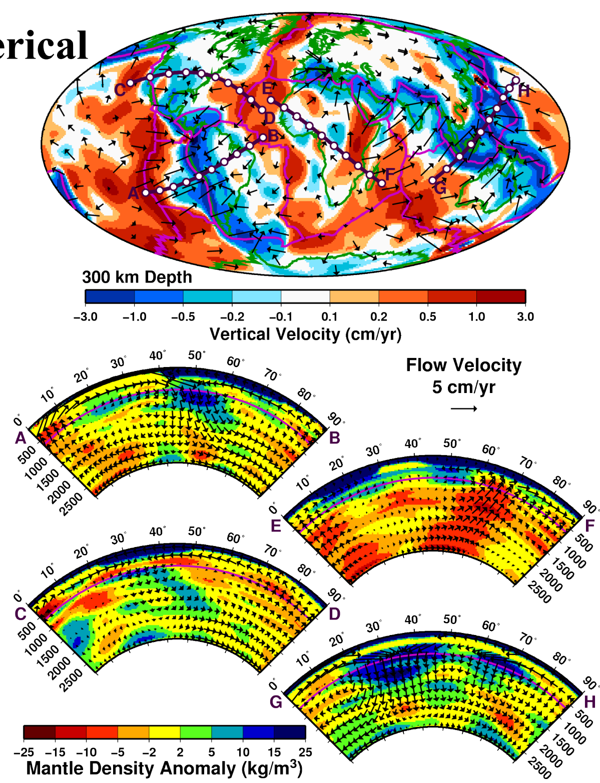


State of the Art: Adaptive Mesh Refinement & Slabs

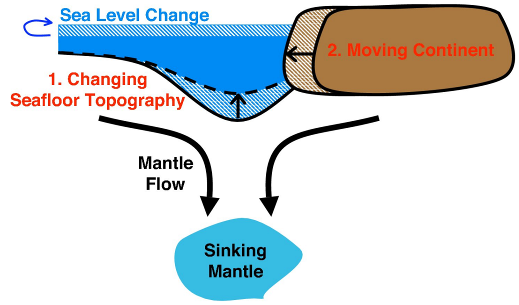
Stadler et al., Science 2010



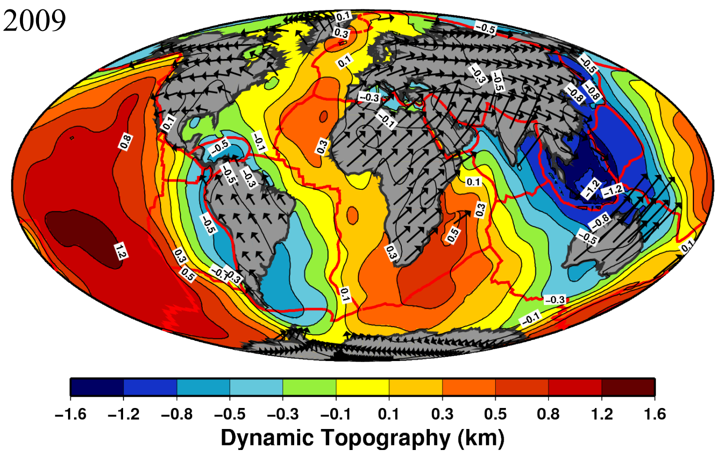
Predictions of Numerical Convection Models: Mantle Flow Field



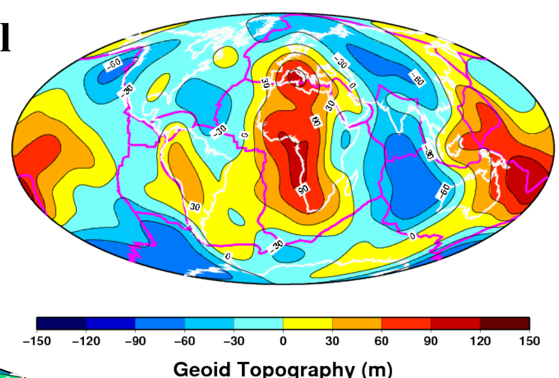
Predictions of Numerical Convection Models: Dynamic Uplift



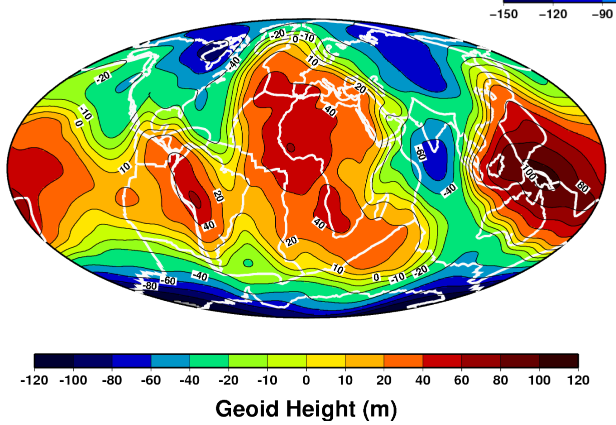
Conrad & Husson, 2009



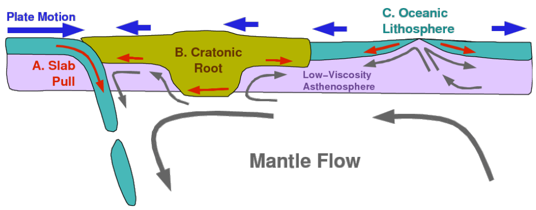
Predictions of Numerical Convection Models: Earth's Shape (the Geoid)

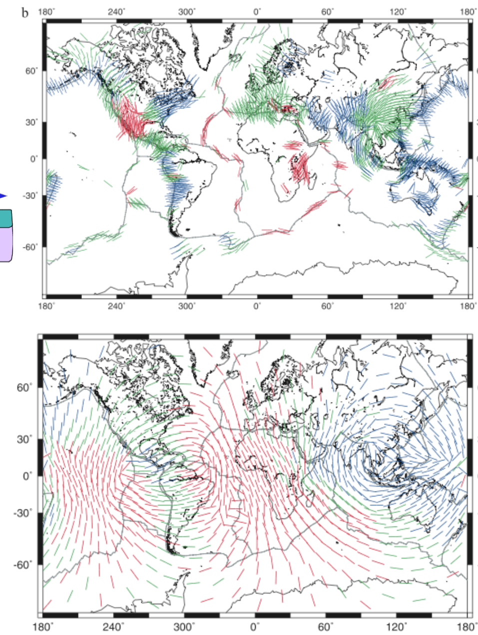


Observed Geoid (grimc)



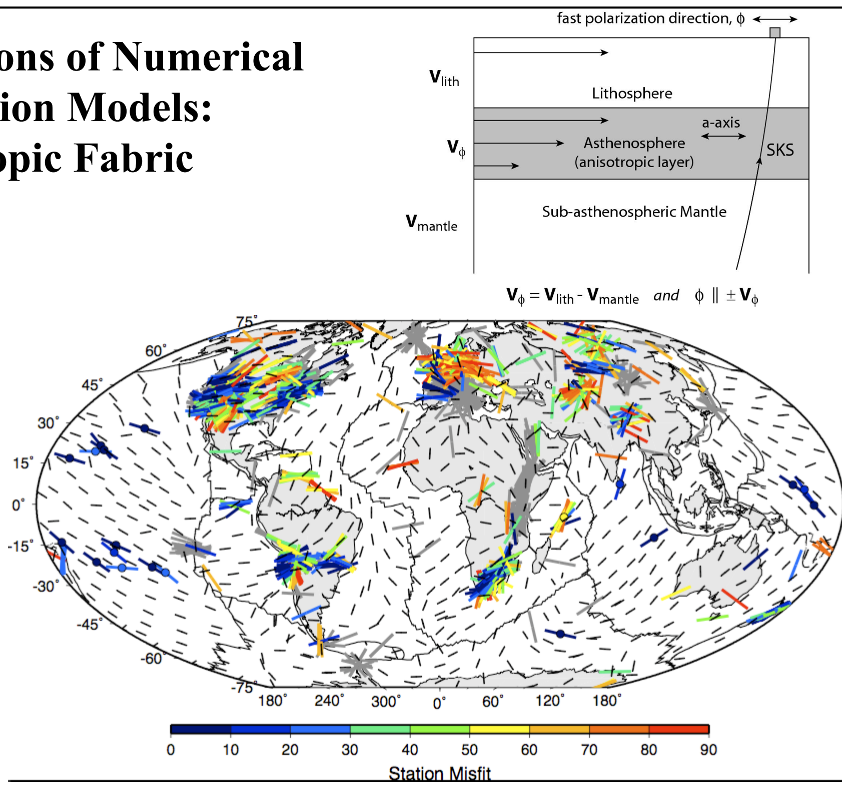
Predictions of Numerical Convection Models: Lithospheric Stresses





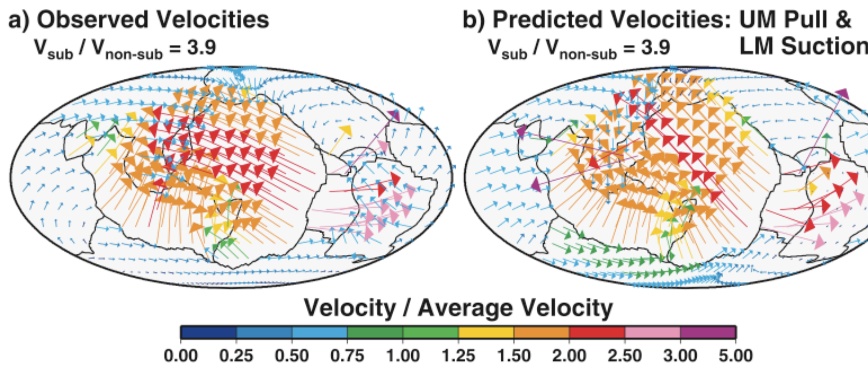
Lithgow-Bertelloni & Guynn, 2004

Predictions of Numerical Convection Models: Anisotropic Fabric



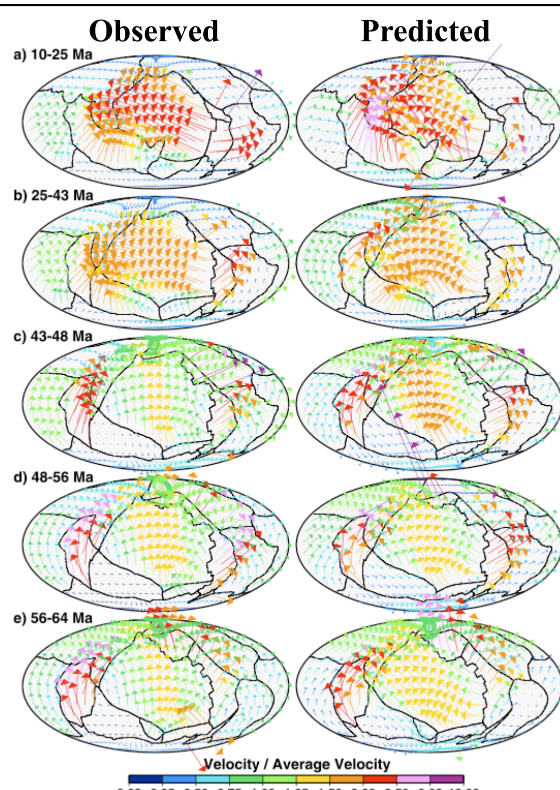
Conrad et al., 2007

Predictions of Numerical Convection Models: Plate Motions



Conrad & Lithgow-Bertelloni [2004]

Predictions of Numerical Convection Models: Time-Dependence of Plate Motions



Conrad & Lithgow-Bertelloni [2004]

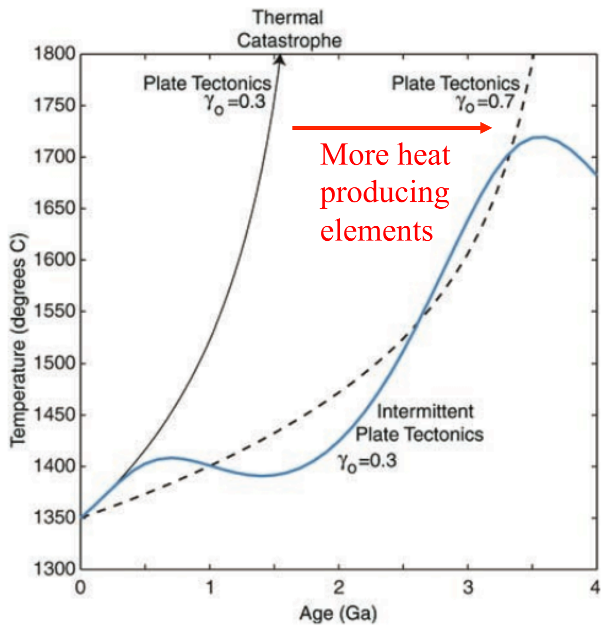
Models of Earth's Thermal History: Heat flow ~ $Ra^{1/3}$

We know the present cooling rate from Earth's heat flow

We estimate the volume of heat-producing elements

Problem: models give a hot start to the earth at 1.5 Ga (!)

Solutions:
→ Deep reservoirs of heat producing elements
→ Plate tectonics is somehow less efficient



Silver & Behn [2008]